THE AMERICAN
JOURNAL OF PSYCHOLOGY
Founded by G. STANLEY HALL in 1887
VOL. XIX OCTOBER, 1908 No. 4

NORMAL PERFORMANCE IN THE TAPPING TEST

BEFORE AND DURING PRACTICE, WITH SPECIAL REFERENCE TO FATIGUE PHENOMENA

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This is an attempt to further standardize a psychological measure of a relatively high degree of simplicity, precision, and responsiveness. The measure is that of the maximum rate of repeated voluntary movements, as described and reviewed in a previous paper.[1] The taps are executed upon a telegraph key which is in circuit with a Porter signal magnet recording on smoked paper upon the 50 cm. drum of a standard Ludwig-Baltzar kymograph. The speed of the drum is approximately 13 mm. per second, the second intervals being directly recorded by a Jaquet chronograph adjusted to the pen of the magnet. The subject is left free to choose the preferred method of tapping, care being taken to see that the method is not essentially altered during the experiment. Attention has been called to sources of error in this freedom of procedure but these can hardly be obviated without introducing other and more important errors. Then too, an important object of the experiments was to obtain normal data for comparison with pathological cases unamenable to more rigid experimental control.

The conduct of the experiment is as follows. The subject begins at a given signal and taps at the maximum rate until a record of 30 seconds is obtained, when he receives a signal to stop. Then follows a 2′ 30″ pause, after which a second series is executed, then another 2′ 30″ pause and so on until five series of 30″, each with an intervening pause of 2′ 30″

[1] *American Journal of Psychology*, Vol. XIX, 1908, pp. 345-58.

have been obtained. A similar record of five 30″ series is then made with the left hand, and in repeated experiments the hands alternate in precedence from experiment to experiment. The subject refrained from muscular effort during the pauses, except that in the experiments in which the writer played the rôle of both subject and operator, the spring of the kymograph was wound with the other hand than that used for the tapping. The 2′ 30″ pause was practically a chance selection, and no attempt has been made to determine the relative influence on the test of pauses of shorter or longer duration.

The experiment is evaluated by counting the number of times the key is struck and the circuit closed during each of the six intervals of 5 seconds in the 30 seconds tapping. If, as sometimes happens, it can be established that the key was struck without closing the circuit, this is counted as a tap. The period of 5 seconds was selected because it has been that most frequently used by previous investigators of the test, and we know more about it in terms of 5 second performances than in any other terms. From the writer's results, which extend considerably beyond the material to be reported here, it is doubtful if any more efficient system of evaluation could be selected for the purposes in hand. To illustrate more clearly the precise method of dealing with the data there may be quoted in full the figures of a sample record with the right hand upon a normal individual, near the limit of practice.

	1st Interval 0–5″	2nd Interval 5″–10″	3rd Interval 10″–15″	4th Interval 15″–20″	5th Interval 20″–25″	6th Interval 25″–30″	No. of Taps in each Series
1st Series	41	37	35	34	34	32	213
2nd Series	41	37	36	35	34	34	217
3rd Series	40	39	37	37	35	34	222
4th Series	40	39	37	36	36	35	223
5th Series	41	39	38	37	36	36	227
Average of Intervals	40.6	38.2	36.6	35.8	35.0	34.2	

"Total Efficiency" of Record **220.4.**

Each of the thirty 2-place figures gives the number of taps executed in an interval of 5 seconds. Reading the top line from left to right we obtain a gradual decrease in the size of the figures, indicating a slowing up in the tapping rate. The right hand figure of three integers, 213, gives the sum of the preceding figures for the six intervals, *i. e.*, the number of taps for the whole 30 seconds. Each successive line may be read in the same way. Considering the figures in column, we obtain the figures of two digits and a decimal on the bottom line (40.6, 38.2, 36.6, 35.8, 35.0, 34.2) the average number of taps executed during the first 5 seconds, the second 5 seconds, etc. Naturally, a regular decrease is noted. The figure in heavy-faced type, **220.4**, gives the average of the five three-digit figures above it, *i.e.*, the average number of taps executed each time during the five 30 second series. This figure is taken as indicating the "total efficiency" of the function in that record, subject, of course, to the variability of the single series it represents. Subsequently, therefore, unless otherwise evident, a two place integer may be taken to represent a number of taps done in a single interval of 5 seconds, a figure of two places and a decimal to represent the verage of number of taps in five cases of a certain 5 second interval. A three place integer indicates a number of taps in a series of 30 seconds, a three place integer with a decimal indicates the average performance in five such series, the total efficiency of the record. Six successive 5″ *intervals* thus form a *series*, five 30″ series a *record*, and the two records of right and left hand constitute the single *experiment.*

The material upon which the present study is based consists of eighty such experiments. Two experiments each were made upon ten normal individuals, and thirty experiments each upon two individuals. One of the subjects in the thirty experiments was the writer; the other was Mr. F. W. Kinsman, a nurse in the hospital, the fidelity of whose co-operation is quite as evident in the figures of his results as it could be made by verbal assurances.

The experiments upon the ten normal subjects were made between 8 A. M. and 2.30 P. M., and the second test was made at the same time of the day as the first, one week later, except in the case of Subject H, in whom the intercurrence of a sprained wrist necessitated a longer interval. The practice curve of the writer consisted of thirty daily experiments broken by intermissions of two weeks after the 14th, and 10 days after the 24th and 26th days. The routine in the other subject was similar, save that his first two days are taken from the records of the ten normal subjects, of whom he was also one. The time of day was not so rigidly controlled as in the

ten subjects, but it fell between 7.45 and 9 A. M. for the former, and between 8 and 10 A. M. for the latter subject. There is evidence that no significant error is induced by this variation.[1]

Inasmuch as the material is to be considered from a number of often only indirectly related points of view, the scope of the discussion may be made clearer by the following enumeration of the points to be brought out. The portions of the study dealing with these various topics have corresponding headings and the main findings on each point are similarly summarized at the close of the paper.

1. Individual differences in "Total Efficiency."
2. Index of right-handedness.
3. Rate in the successive series, "warming up."
4. Rate in the successive intervals, fatigue.
5. Fatigue and individual variation.
6. Total efficiency practice for the two subjects.
7. Relative practice of right and left hands.
8. The effect of practice upon the "warming up" phenomenon.
9. Practice and the successive intervals.
10. The influence of intermissions upon practice gain.
11. The effect of "warming up," as brought out by practice, on the different intervals.
12. An "index of fatigue."
13. Correlation of the fatigue phenomena in the different hands.
14. The relative fatigability of right and left hands.
15. The correlation of fatigability and initial rate.
16. The effect of practice on fatigability.
17. Variability.
18. The subjective condition as related to gross rate and fatigability.

1. Individual Differences in "Total Efficiency." The following table gives for the ten subjects the gross rate in terms of number of taps in a series of 30 seconds, without reference to fatigue phenomena. The series for each hand are arranged in columns of five, according to their order in the record. The figures in heavy faced type give the averages of the figures above or preceding them, according as we consider the average rate of each subject, or the average of the first, second, third, fourth or fifth series in all ten subjects. Thus the aver-

[1]Since the practice of Subject I was necessarily with knowledge of immediate results, it was considered desirable that Subject II should also have an equal knowledge. The present practice is, therefore, "with knowledge of results," but only to the extent of a knowledge of the gross practice gain.

TABLE I.

GROSS RATES IN TEN NORMAL INDIVIDUALS. NUMBER OF TAPS IN 30 SECONDS.

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
First Experiment, Right Hand.												
1st Series	218	153	182	198	192	201	175	216	209	180	**192.4**	*16.0*
2nd "	217	156	175	197	187	195	187	209	201	181	**190.5**	*13.3*
3rd "	221	156	174	201	191	207	192	206	205	185	**193.7**	*14.6*
4th "	229	156	204	204	195	204	189	212	209	186	**198.8**	*13.8*
5th "	209	155	182	215	191	205	192	215	206	186	**199.2**	*14.4*
Average	**218.8**	**155.2**	**183.4**	**203.0**	**191.2**	**202.4**	**187.0**	**211.6**	**208.0**	**183.6**	**194.9**	
M. V.	*5.0*	*1.0*	*8.0*	*5.2*	*1.8*	*3.6*	*4.8*	*3.2*	*2.0*	*2.2*	*3.7*	

age of Subject E's, five series of taps with the right hand in the first experiment is **191.2,** in the second experiment is

TABLE I. (Cont.)

Second Experiment, Right Hand.

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
1st Series	216	147	163	200	199	205	193	212	200	175	**189.0**	*20.9*
2nd "	225	150	158	202	193	202	193	210	204	175	**191.4**	*18.0*
3rd "	239	158	160	202	197	207	202	206	200	180	**195.1**	*17.5*
4th "	242	147	162	208	207	208	203	211	204	178	**197.0**	*20.8*
5th "	234	151	160	207	207	207	192	214	205	182	**195.9**	*19.7*
Average	**231.2**	**150.6**	**160.6**	**203.8**	**200.6**	**205.8**	**196.6**	**210.6**	**202.6**	**178.0**	**193.7**	
M. V.	*8.6*	*3.2*	*1.6*	*3.0*	*5.2*	*1.8*	*4.8*	*2.0*	*2.0*	*2.4*	*3.5*	
First Experiment, Left Hand.												
1st Series	200	132	159	185	167	163	173	198	181	171	**172.9**	*14.3*
2nd "	202	127	161	175	166	166	185	186	185	170	**172.3**	*14.3*
3rd "	206	131	159	171	179	173	170	188	188	174	**173.9**	*13.1*
4th "	203	123	162	173	174	166	175	191	190	167	**172.4**	*14.4*
5th "	199	120	152	176	177	176	177	200	188	168	**173.3**	*16.1*
Average	**202.0**	**126.6**	**158.6**	**176.0**	**172.6**	**168.2**	**176.0**	**192.6**	**186.4**	**170.0**	**173.0**	
M. V.	*2.0*	*4.0*	*2.4*	*3.4*	*4.8*	*3.8*	*4.0*	*5.2*	*2.8*	*2.0*	*3.4*	

TABLE I. (Cont.)

Second Experiment, Left Hand.

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
1st Series	209	138	153	188	187	177	172	197	191	170	**178.2**	*16.8*
2nd "	207	135	159	177	185	167	169	194	190	165	**174.8**	*15.8*
3rd "	221	127	155	180	185	179	171	197	191	167	**177.3**	*17.7*
4th "	213	128	155	169	198	174	174	196	189	163	**175.9**	*19.4*
5th "	220	133	154	177	182	174	168	191	188	165	**175.1**	*15.7*
Average	**214.0**	**132.2**	**155.2**	**178.0**	**187.4**	**174.2**	**170.8**	**195.0**	**189.8**	**166.0**	**176.3**	
M. V.	*5.0*	*3.8*	*1.4*	*4.6*	*4.2*	*3.0*	*1.8*	*2.0*	*1.0*	*2.0*	*2.9*	

200.6, but the average number of taps of all subjects during the first series for the right hand is **192.4** in the first experi-

ment and **189.0** in the second. Let us first consider the gross rates of the various subjects as given in the heavy faced figures running horizontally across the table.

It is difficult to estimate the range of individual differences because the limit is not well defined. The rates of rhythmic discharge in tonic contractions obtained by Schaefer and others have been surpassed in repeated voluntary movements. The fastest initial rate on record is, I believe, about 15 per second. Our rates here are much slower, the fastest and slowest subjects, who happen to be the first two quoted, vary as about 3:2. With a greater number of subjects, we should doubtless have increased this range.

It will be remembered that Bolton, working with large groups of children found a group correlation between a general superiority of make-up and the gross rate of tapping. Bagley did not find it for class standing. What correlations in this respect may obtain for groups, the present observations are not of a character to say, but as between individuals they are altogether insufficient to serve as a basis for deductions as to any phase of physical or psychical constitution. W. G. Smith[1] mentions that among his fastest subjects were epileptic dements; the fastest record but one obtained by the writer is from a well developed case of general paralysis. The writer has observed a few individuals who, tapping unusually fast, without special practice, were of highly "nervous" temperament, but equally "nervous" temperaments may be found among those whose maximum rate is below the average.

What is the precise physiological significance of the maximum rate is by no means well made out, and cannot be deeply entered into here. It seems to be generally conceded that it is limited by the refractory phase of the synapses in the motor pathways, but that does not make the tapping test a measure of the period of this refractory phase; at least not in the earlier stages of practice. It is probable that the measure of this period would give us data of considerable psychological significance, and it may be possible to study it through the methods described by Schaefer and others. In the later stages of practice we probably do obtain in the tapping test a measure greatly analogous to this, but in the beginning, as we ordinarily have to apply the test, the factors in speed are probably those of co-ordination mainly,[2] and cannot be expected

[1] *Br. J. Ps.*, I, 256.

[2] In so far as the graphic record of the manipulation of the telegraph key affords an analysis of the tapping movements, it brings out a rather interesting point with respect to the nature of this co-ordination. The record gives of course, the time during which the key is held down distinct from that during which it is released. In Subject

to afford information about the condition of the motor pathways as given in the refractory phase. A high gross rate in tapping does not, as has been pointed out, involve superiority in other aspects of motor speed. It may be mentioned that the writer happens to be at about the limit of practice in both the tapping test and simple reaction time. In simple reaction time (to sound and light) he has always been quite rapid; in the tapping test relatively slow. If the different aspects of motor speed do not correlate with each other, we certainly cannot expect a single aspect to give us a general idea of the individual's motor speed. The tapping test happens to be the easiest of the motor speed tests to make with a fair degree of accuracy, and it is probably as fundamental a point of individual difference as any other psychological test. At present it measures ultimately no more than it measures immediately, and indicates "voluntary motor ability" only in a very Pickwickian sense. Nevertheless the bare statistics of previous and the present experiments would seem to give assurance that there are conditions, almost certainly nervous, with which performance in this test varies from day to day and from individual to individual considerably beyond the limits of probable error. As these conditions are better made out, the gross rate will assume greater significance. At present, it is

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I the ratio of the pressed down period to the released period was about the same in right and left hands, and an immediate effect of practice was to decrease it very markedly, and about equally for both hands; that is, so far as can be judged by inspection, the key appears to be held down for a proportionately shorter period of the entire tap after practice than before. In Subject II it was also quite noticeable that the holding-down period decreased with practice in the right hand, and that it was from the beginning shorter in the right than in the left. Practice tended to make this difference more marked; the holding-down period decreased much more in the right hand than in the left. Indeed, one can hardly be sure that it decreases in the left hand at all. The length of this holding-down period varies a good deal from day to day, but as between the records of the same day, it becomes much more constant with practice. The length of this holding-down period may perhaps be taken to represent in a measure the efficiency of co-ordination, for the hand should obviously come up as soon as it touches the key; the direction of the hand's movement must be changed with as little loss of time as possible. The effect of practice is to shorten this interval, but above all to make it more constant, which latter is perhaps the truer attribute of efficiency in co-ordination. It may be mentioned that Binet and Vaschide with the myograph method found the pause between contraction and relaxation (corresponding to the holding-down period) to be longer than that between relaxation and contraction, though this result is incommensurable with the present experiments, since both movements here involve muscular contractions. With certain obvious modifications in method, the test might afford very interesting data in the improvement of rapid co-ordinations by practice.

impossible not to regard the changes in rate within the individual performance as the more important factors. Its technical advantages as a measure of fluctuation in continued work have been previously discussed.

2. *Index of right-handedness.* Woodworth has proposed an "index of right-handedness" based on the ratio of the efficiency of the left hand to that of the right. Our criterion of efficiency in this case is the average number of taps executed during five series of 30 seconds each. Dividing the average for the left hand by the average for the right, we obtain the "index." These indices for each of the ten subjects in the two experiments are as follows:

TABLE II

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
First experiment (right hand preceding.)	.93	.81	.87	.87	.90	.93	.94	.91	.90	.93	**.89**	*.035*
Second experiment (left hand preceding.)	.93	.87	.96	.87	.93	.85	.87	.93	.93	.93	**.91**	*.033*

In the average the left hand does relatively better when it precedes than when it follows the right, which would be the case if the work with one hand had a fatiguing effect upon the speed of the other, but in the individual cases this is seen to be the product of certain coarse deviations in either direction, so that no general conclusion ought to be drawn. For the subjects who do remain fairly constant, however, the individual differences in the index are worth noting.

3. *Rate in the successive series, "warming up."* We may now consider the data of Table I according to the heavy-faced figures in the vertical columns, the averages of the total efficiency for each 30″ series taken by itself. In the right hand it is quite noticeable that the first two series are generally the poorest, and that there is a well-marked tendency for the later series to be faster than the earlier. To this phenomenon we may apply the name of *interserial warming up, i. e.*, a warming up from series to series, as distinct from a warming up process confined to a single series. The only trace of this latter process in normal individuals seems to be a slight increase in rate during the first second. This interserial warming up really appears

much more strikingly in the examination of the records of the individual subjects than it does in the averages, where it is entirely masked by the size of the m. v.'s. The tendency to progressive improvement can easily be traced throughout the right hand.

In the left hand it is by no means so evident that such a process exists. In the first experiment the five series average about equal in rate, and are very close together. In the second they are also quite close, the first series this time averaging the best. Some records seem to warm up, others to fatigue between the series, but on the whole the order is rather chaotic. The m. v.'s of these averages are an expression of individual difference between the subjects. It will be noted that these variations were distinctly greater in the second test than the first. This might possibly be taken to indicate that interest in the test was more nearly equal in the first than in the second experiment. Conscientiously co-operative individuals will work equally well up to their maximum at both times; on the other hand those subjects to whom novelty contributes the chief interest in the test, will co-operate better the first time than the second. Individual differences in the hands are practically equal, though they are slightly less in the left, not enough so for any special interpretation.

4. *Rate in the successive intervals, fatigue.* Let us now consider the data as presented from a different viewpoint, *i. e.*, according to the rate in each of the six successive 5″ intervals. (See Table III.) Since each series provides one of each interval, and the series are five in number to the record, each figure in the subjoined table gives the average number of taps during five cases of each five second interval. The precise way in which the figures are calculated may be understood by referring to the type record (p. 438). What 40.6, 38.2, 36.6, 35.8, 35.0, 34.2, are to the subject in the type record, 41.2, 38.8, 35.8, 35.0, 33.8, and 34.2 are to Subject A's first record with the right hand. During the first five seconds of each of his five series he averages 41.2 taps, during the second five seconds 38.8 taps, during the last five seconds 34.2 taps. As above, the figures are quoted separately for each of the two experiments. The average rates of the ten subjects for each interval as well as their m. v.'s will be found in their usual places.

Through these figures we may obtain an idea of the progressive decrease in efficiency which we term the fatigue loss. It appears that, so far as can be gathered from discrete units like the present, the curve follows the form usual to fatigue curves, the decrease being rapid at first and subsequently slower. The method is not such as to make it worth while to undertake measurements of very fine fluctuations; some

The figures are as follows :

TABLE III

RATES IN THE SUCCESSIVE INTERVALS IN TEN NORMAL INDIVIDUALS

AVERAGE NUMBER OF TAPS IN 5 CASES OF EACH INTERVAL

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
First Experiment, Right Hand												
1st interval	41.2	27.6	32.8	36.2	36.4	37.2	32.0	38.6	39.0	32.4	**35.3**	*3.3*
2nd "	38.8	27.0	31.0	34.6	33.8	34.2	31.6	36.6	35.8	31.6	**33.5**	*2.6*
3rd "	35.8	26.0	31.0	33.8	31.8	33.6	31.2	35.6	34.4	30.6	**32.3**	*2.3*
4th "	35.0	25.2	29.6	33.2	30.0	33.6	30.8	34.4	33.6	30.2	**31.5**	*2.4*
5th "	33.8	24.8	29.4	32.6	29.8	32.4	31.0	33.4	33.0	29.6	**31.0**	*2.0*
6th "	34.2	24.6	29.6	32.6	29.4	31.4	30.4	33.0	32.2	29.2	**30.7**	*2.0*

TABLE III. (Cont.)

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
Second Experiment, Right Hand												
1st interval	43.8	28.0	27.0	35.8	39.0	36.0	34.2	37.8	37.4	30.6	**35.0**	*3.9*
2nd "	40.0	26.6	27.2	34.6	35.4	34.4	33.0	36.0	35.0	30.2	**33.2**	*3.1*
3rd "	37.6	24.8	26.4	34.0	33.0	33.8	33.2	35.4	34.0	29.6	**32.2**	*3.2*
4th "	36.8	23.8	27.0	33.4	31.4	33.6	32.8	34.8	32.6	29.4	**31.6**	*2.9*
5th "	37.0	24.0	26.6	33.4	31.2	34.2	31.8	33.8	32.2	29.4	**31.4**	*2.9*
6th "	36.0	23.4	26.4	32.6	30.6	33.8	31.6	32.8	31.4	28.8	**30.7**	*2.8*
First Experiment, Left Hand												
1st interval	40.8	23.6	27.6	32.2	30.2	32.0	32.4	35.8	34.2	31.2	**32.0**	*3.0*
2nd "	37.0	22.0	27.2	30.6	29.2	29.6	30.2	33.8	32.4	29.4	**31.1**	*2.9*
3rd "	33.6	20.2	26.6	29.0	29.4	28.0	29.8	31.8	30.8	28.2	**28.7**	*2.4*
4th "	30.6	20.4	26.0	28.6	28.2	27.0	28.4	31.6	29.8	27.8	**28.0**	*2.1*
5th "	30.8	20.4	25.6	28.2	27.8	26.2	28.0	29.6	29.6	26.8	**27.3**	*2.2*
6th "	29.2	20.0	25.6	27.4	27.8	25.4	27.2	30.0	29.6	26.6	**26.9**	*1.9*

TABLE III. (Cont.)

Second Experiment, Left Hand

Subject	A	B	C	D	E	F	G	H	J	K	Av.	M. V.
1st interval	42.8	24.4	26.6	32.4	34.0	32.0	30.4	35.2	35.0	29.8	**32.3**	*3.5*
2d "	38.2	23.4	26.0	30.4	33.0	30.6	30.2	34.8	32.6	28.6	**30.8**	*3.2*
3rd "	34.6	21.6	26.0	29.8	31.2	28.8	29.0	32.4	31.6	27.8	**29.3**	*2.6*
4th "	33.6	21.0	25.8	29.0	30.2	28.0	28.2	30.2	31.0	27.0	**28.3**	*2.4*
5th "	32.4	21.0	25.6	28.2	29.6	27.8	27.0	32.2	30.2	26.6	**28.1**	*2.3*
6th "	32.4	20.8	25.2	28.4	29.4	27.0	26.0	30.2	29.4	26.2	**27.5**	*2.3*

rather limited researches upon this point have already been mentioned.[1] Great individual differences in the regularity of the single taps can be seen, however, by inspection, and this is an aspect of the test that would well repay special study, though it is not within the scope of the present calculations. It may also be brought to mind that as the figures given are averages, the decreases which they represent are frequently of greater regularity than characterizes the scores for the individual series, the irregularities tending to compensate; but the averages also compensate for the error introduced by taking no account of fractions of a tap, which, when the rates are very constantly maintained, is often of no inconsiderable significance.[2]

5. *Fatigue and individual variation.* So far as gross rates are concerned, the figures of course merely restate the data given in Table I; but the m. v.'s seem to present unequivocally a point of some significance. It will be noted that they throughout tend to become progressively smaller as fatigue sets in, quite out of proportion to the decrease in gross rate. This is true of all the records.

The individual differences in the function are decreased by from 1/4 to 1/3 after 30 seconds work. *The main factor then, in giving a high gross rate to an individual at the beginning of practice is his performance in the earlier intervals.* When we are

[1]Bliss: Yale Studies, I, 45-52; Moore: Yale Studies III, 92-95.

[2]There must be mentioned in this connection a series of eight experiments with an additional mentally normal subject, with no known neurological condition, who fails entirely to show any of the principal phenomena of the tapping test indicated as normal in these and previous studies. Of co-operation, at least to the level of that reached in any of the ten normal subjects, there can be no question. The results are marked by very wide fluctuations between the intervals as well as from series to series, and even from day to day. Of fatigue phenomena, in the sense in which the term has been here used, there is no significant trace, but as has been said, there are very wide, almost chaotic fluctuations, between the intervals. Examples are such series as the following:

a.	*38*	*40*	*35*	*39*	*35*	*36*
b.	*40*	*38*	*37*	*40*	*39*	*38*
c.	*34*	*33*	*35*	*40*	*40*	*38*
d.	*36*	*36*	*36*	*36*	*38*	*36*
e.	*30*	*31*	*32*	*31*	*36*	*32*

Now and then occurs a series whose intervals resemble the familiar fatigue curve, as 34, 33, 31, 29, 29, 29, but this no oftener than might be the product of chance. Indeed, if there is any general tendency at all it is for the later intervals to be faster than the earlier, *i. e.*, they show intra-serial warming up, warming up within the series. During the eight consecutive days there is no trace of practice; indeed, the later experiments are rather slower than the earlier. The writer cannot formulate any explanation of these wholly anomalous records.

fresh, and doing the best that we shall do, we vary distinctly more from each other than when we have lost somewhat through fatigue. The nearest interpretation might again seem to be in terms of co-operativeness. The more co-operative individuals tried harder, and fatigued more quickly to the level of those who did not try so hard. In this sense however, we have to interpret co-operativeness, not in terms of consciousness, but rather as the amount of effort which the organism puts forth in response to volition. It may be said with some assurance that continued exercise of the function, besides lowering its efficiency, tends also to decrease individual differences in it.

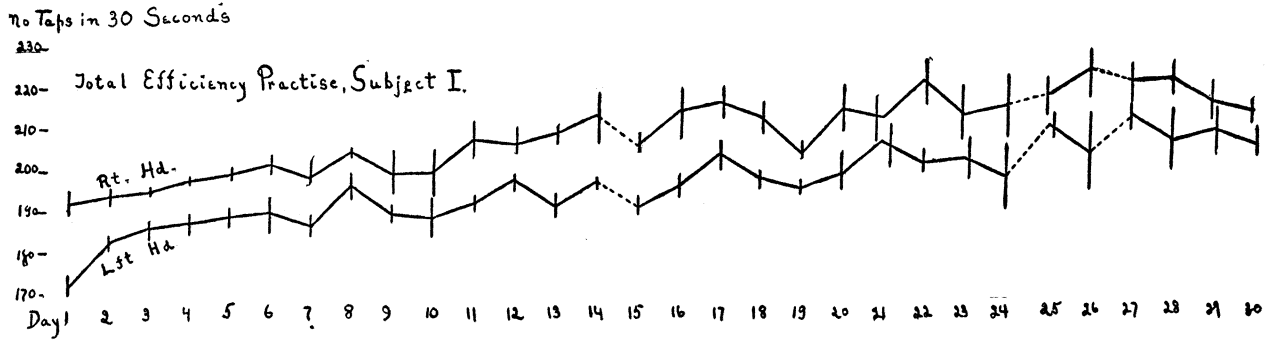
6. *Total efficiency practice for the two subjects.* Such are the general phenomena of the tapping test as they appear in ten normal individuals without special practice. We shall now observe how these conditions are modified during practice in two normal individuals. As has been said, the series on Subject I is continuous except for intentional breaks in practice, but the first three experiments on Subject II were separated by considerable intervals which do not, however, appear to affect their results. In each subject intermissions of 14 days were introduced after the 14th and of 10 days after the 24th and 26th days; this being done to study the effect of such intermissions on the practice curve. The entire curve is made up of 30 experiments.

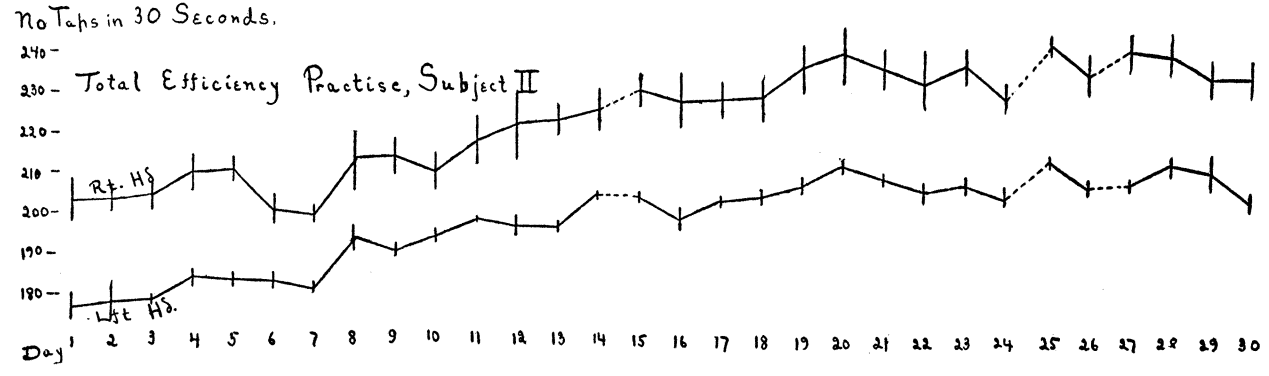
As a basis for plotting the general course of the practice curve in the two subjects, the natural choice fell upon the "total efficiency" figure for each record, corresponding to **220.4** in the type record. The accompanying plate shows the practice curve as given for the successive thirty "total efficiency" figures. The dotted lines, here and in Plates II and III, mark the intermissions. The vertical lines give the m. v. of each total efficiency figure.

It should perhaps be mentioned that Subject I had had some relatively unsystematic practice in the test, both as a subject in other researches of which it formed a part, and in setting up the present apparatus. Subject II was quite without special practice. The curves, however, show no characteristic that could be referred to this difference.

First of all, it will be noted that the rise of the curve is not more rapid at the beginning than elsewhere, the opposite of what we usually expect in practice curves. This is especially marked in Subject II, in whom we should expect it least, as he was without special practice; there is even a distinct drop in efficiency before a significant practice gain begins. This would seem to indicate that such unsystematic practice in this function as we receive in normal life largely eliminated the

PLATE I


No Taps in 30 Seconds
Total Efficiency Practise, Subject I.
Rt. Hd.
Lft Hd.
Day


No Taps in 30 Seconds.
Total Efficiency Practise, Subject II
Rt. Hd.
Lft Hd.
Day

marked gains so frequently seen at the beginning of practice curves. Strictly speaking, there is of course no function in which we can get the real beginning of a practice curve, any more than we can ever be really certain of having reached its end. The last ten experiments on both subjects show no especial practice gain, and so far as they go indicate the limit of practice to have been reached; but in a series of later experiments, not reported here, separated from these by an interval of nearly a month, a distinctly higher rate is obtained with Subject I. The same might or might not be true of Subject II.

7. *Relative practice of right and left hands.* Again, in neither subject does the left hand show an improvement relative to the right. In Subject I the index of right-handedness remains practically the same. In Subject II the right hand may even improve more than the left. So far as this function is concerned then, the asymmetry does not seem to be a matter of practice, at least during adult development. If it is such during earlier years, and there are so far as I know no data on this point, it might indicate that the organism is no longer sufficiently plastic to respond differently according to differences in previous training, yet it is difficult to see how under such conditions the hands would respond to practice at all, as they certainly do. At the present time the superiority of the right hand in this function seems permanently "set;" whether it was formerly otherwise is not a question which these data can answer.

In Subject I the left hand curve for the first twenty experiments follows the right very closely from day to day, rising and falling with it in every case but two (12th and 13th days), often in much the same ratio. This would indicate that the conditions bringing about a rise or fall in rate were of a general nature, since they tended to affect both hands similarly. On the 21st day, however, precisely the reverse condition begins, and is maintained to the end of the experiments save for the 30th day. The indices, as is evident below, show that the approach to this condition was gradual. When the right efficiency increases, the left decreases, and *vice versa*. It will be remembered that the precedence of the two hands alternates from day to day. Under these later conditions each hand does relatively better when it *follows* the other hand than when it precedes. It is as though the work done with the preceding hand effected a generalized warming up, contributing to the greater efficiency of the following hand.

The record of Subject II shows the same general correspondences, though with rather more frequent exceptions, seven in number. There is no evidence of the generalized warming-up

at the end, as in Subject I. On the whole, then, the tapping rate seems to be the expression of a general condition.

It will be noted that Subject I's performances for the first seven days vary very little among themselves, the curve being almost a straight line, slightly ascending. At this point we begin to encounter relatively wide fluctuations from day to day, which continue throughout the experiments. In Subject II this is also seen in the left hand; not so well in the right. Such an appearance would indicate that at the beginning a fairly constant limit was set to the maximum rate, which was later superseded by another limit of a much more variable character. The first limit may be one of co-ordination; the second, one of the actual discharge rate of the nervous impulses, but this is purely hypothetical.

From these data it follows that the index of right-handedness should not be subject to any marked increase or decrease as an effect of practice. The indices in each of the thirty experiments for both subjects are given on Table IV, p. 456.

In Subject I the average does not essentially change, and the low index in the first experiment is probably accidental. Nevertheless there is another point of interest. It may be noted that beginning with the 16th experiment the size of the index alternates quite regularly from high to low, although this is not strikingly apparent in the practice curves till the 21st day. The high index, *i. e.*, the relatively greater efficiency of the left hand occurs when the right hand precedes the left in the experiment. This is not shown by Subject II, whose indices are very constant from day to day, and indeed throughout, though they seem to rise slightly during the second five days.

The hands are very much closer together in Subject I than in II. The right hand of I does not improve in practice so much as that of II, nor does the left, if we do not consider I's first day. The difference is, however, very small, and in relation to the gross rates quite negligible.

It is safe to say that the intermissions, indicated by dotted lines, could not be located unless they had been so indicated. But while the intermissions do not essentially affect the gross rate as given in the figures here presented, they do affect the performance considerably, as more detailed considerations will subsequently show.

The m. v. of each day's series among themselves tends to increase as shown by the increase in the length of the vertical lines. Practice is ordinarily supposed to bring m. v.'s down, and it very probably does decrease that of the individual taps for short periods, but as between series and series, it introduces a warming up effect that increases their m. v. To what ex-

TABLE IV

Exp. (Day)	1	2	3	4	5	6	7	8	9	10
Subject I.	.90	.94	.96	.95	.95	.94	.93	.96	.95	.94
Subject II.	.87	.87	.87	.88	.87	.91	.91	.91	.89	.92
Exp. (Day)	11	12	13	14	15	16	17	18	19	20
Subject I.	.92	.96	.92	.92	.93	.92	.95	.93	.96	.92
Subject II.	.91	.88	.88	.91	.88	.87	.90	.89	.88	.89
(Exp. Day)	21	22	23	24	25	26	27	28	29	30
Subject I.	.97	.91	.95	.92	.97	.91	.96	.93	.97	.96
Subject II.	.88	.89	.87	.87	.88	.88	.86	.89	.90	.87

tent the increased m. v. is due to this factor may be gathered by comparing the other three curves to that of Subject II's.

left hand. The warming up increase is practically absent here as is also the progressive increase in the m. v.

8. *The effect of practice on the "warming up" phenomenon.* So much for the general effect of practice on gross efficiency. In further analysis we must determine the special way in which this increase manifests itself, whether it occurs through a general increase in efficiency throughout the fatigue curve, or is mainly a heightening of the initial rate, or the giving of a progressive immunity to fatigue. Also whether the increase manifests itself differently in different series, the earlier series of an experiment not gaining so much as the later, or what not. This is the point that we shall consider first, and the data bearing upon it are given in Table V, pp. 458-9.

In this table the thirty experiments are divided into three groups of ten each, the figures in the vertical columns giving the average and m. v. of each series from day to day for each set of ten. There will at once be noted a perfectly definite tendency for the later series in each experiment to be faster than the earlier, that is, the efficiency of the hand warms up during the experiment. Inasmuch as the last series is almost always the fastest, we cannot say from these experiments how far the warming up process would extend, or how much further increase there might be.

When we observe this warming up process as it appears in the successive groups of ten experiments, it is evident that the warming up, (*i. e.*, the balance in favor of warming up over persistent fatigue) is very much accentuated by practice. In the ten normal individuals we could observe its presence in the right hand even without special practice, but by no means so distinctly as it appears in the tables here. In Subject I there was really no trace of the warming up until the fourth or fifth experiment, though in the right hand of Subject II it was quite evident from the start. The increase tends to become progressively greater with each group of ten, and the phenomenon is much more clear in the individual records than the m. v.'s of the averages would indicate it to be. The day to day variation in gross rate brings up the m. v.'s without really affecting the relation in which the different series of the same day stand to one another. This can be seen in another way. It will be noted that while the difference between the successive series of the same day (as given in the m. v., Plate I, vertical lines) tends to increase with practice, the m. v. of the same series on successive days (Table V) tends to decrease with practice; the day to day performance in each series tends more and more to form a species within itself.

The influence of practice in bringing out the warming up process could not be fully shown without printing the entire

set of series in full, which is hardly worth while; nevertheless some further demonstration of the fact may be found in the

TABLE V

Average number of Taps in each of the five successive 30″ Series, for the first 10, the second 10, and the third 10 days of the thirty experiments. The M. V. gives the day to day variations of each series.

Subject I

	Rt. Hd.						Lft. Hd.					
Days	1–10.		11–20.		21–30.		1–10.		11–20.		21–30.	
	Av.	M. V.	Av.	M. V.	Av.	M. V.	Av.	M. V.	Av.	M. V.	Av.	M. V.
1st series	194.6	**3.6**	204.3	**3.5**	209.5	**4.1**	184.6	**3.7**	194.3	**2.6**	197.3	**5.1**
2nd "	195.4	**4.4**	206.5	**3.1**	213.7	**3.7**	183.8	**4.7**	192.9	**2.9**	202.3	**3.8**
3rd "	197.7	**3.9**	212.7	**4.3**	221.5	**3.7**	188.4	**6.2**	198.9	**3.7**	207.7	**3.1**
4th "	200.8	**3.1**	215.4	**4.8**	223.6	**2.2**	188.9	**4.5**	199.5	**4.0**	211.9	**5.5**
5th "	201.1	**5.5**	218.6	**4.5**	224.9	**3.7**	189.1	**4.7**	200.2	**3.4**	212.7	**3.1**
Average	**197.9**	**4.1**	**211.5**	**4.0**	**218.6**	**3.5**	**187.0**	**4.8**	**197.2**	**3.3**	**206.4**	**4.1**

TABLE V. (Cont.)

Subject II

Days	Rt. Hd. 1–10. Av.	M. V.	11–20 Av.	M. V.	21–30 Av.	M. V.	Lft. Hd. 1–10 Av.	M. V.	11–20 Av.	M. V.	21–30 Av.	M. V.
1st series	201.2	3.8	217.2	4.4	227.0	2.4	187.2	4.4	203.8	4.8	209.1	2.6
2nd "	203.5	4.5	224.6	6.0	232.9	3.9	182.2	4.6	200.7	4.5	206.3	3.9
3rd "	207.5	5.5	230.3	5.3	237.0	3.7	184.8	6.0	203.6	4.4	210.0	4.3
4th "	210.9	6.5	234.2	4.4	240.7	3.5	183.5	6.4	203.4	3.8	207.7	2.7
5th "	213.9	5.1	234.6	5.8	242.4	3.6	184.9	5.9	203.5	3.5	206.4	2.8
Average	**207.4**	5.1	**228.2**	5.2	**236.0**	3.4	**184.5**	5.5	**202.9**	4.2	**207.9**	3.3

following curves, which represent the right hand practice through the thirty days for the first and last series of each day

PLATE II

Practice curves of the 1st and 5th series of the right hand in each subject. The warming up from the 1st to the 5th series, and its accentuation by practise, are shown by the curve for the 5th series drawing away from that of the 1st series.

(corresponding to 213 and 227 in the type record), just as the practice curves previously quoted gave the average of all five series. As before, the dotted lines mark the pauses. It will be noted that the curve for the last series draws away from that of the first, showing its more rapid increase in rate. The practice gain in Subject I and in the right hand of Subject II are thus seen to consist largely in the increase in rate of the later series over the ealier.

In the left hand of Subject II this warming up is not in evidence, but this does not mean that it is absent. We must always bear in mind that we never study fatigue alone, or warming up alone, but the resultant of the two, and it is according as one overbalances the other that we speak of the work as showing "warming up" or "fatigue." It is perfectly possible that the conditions of warming up are potentially present but are overbalanced by fatigue conditions; so far as sensations go this would be borne out by the introspection of the subject, who never entirely lost a progressive sensation of fatigue in the left hand record. In Subject I the left hand showed no more tendency to fatigue sensation than the right after the first few days of practice. It will be remembered that also in the ten subjects the warming up was much more marked in the right hand than in the left. This would be in accord with the result of practice as bringing out warming up, since in these subjects also the right hand was presumably more practiced for this function than the left.

9. *Practice and the successive intervals.* Now given the result that the practice increase of the "total efficiency" figure comes in as an increase of the later series rather than of the earlier, what is the character of the gain in the intervals of the individual series itself? Is it an approximately equal gain for all intervals, is it an increase in initial efficiency or is it an increase mainly in the later intervals through growing immunity to fatigue?

With reference to this point we must consider the data in the same way as they were presented for the ten normal subjects in Table III, *i. e.*, interval by interval. The experiments have again been divided into 3 groups of 10, the averages and m. v.'s for each successive interval being given in Table VI, pp. 462-3.

10. *The influence of intermissions upon practice gain.* The most interesting aspect of practice phenomena, however, is afforded in a study of the effect of intermissions. The days after the intermissions are, as noted, the 15th, 25th, and 27th days. Referring to Plate I we see that in total efficiency these days show for Subject I a uniform loss with the right hand; with the left, however, there is a loss only with the first intermission,

TABLE VI

Number of Taps in each of the successive 5″ intervals. Average of 50 cases of each interval, 5 for each of ten days. The M. V. gives the day to day variation of the averages for the 5 cases of each interval for each day.

Subject I

Days	Rt. Hd. 1–10		Rt. Hd. 11–20		Rt. Hd. 21–30		Lft. Hd. 1–10		Lft. Hd. 11–20		Lft. Hd. 21–30	
	Av.	M V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M. V.
1st interval	36.4	**1.04**	39.2	**.80**	40.8	**1.06**	34.2	**1.06**	36.1	**.94**	38.1	**.76**
2nd "	34.7	**.52**	37.2	**.62**	38.8	**.50**	32.7	**.79**	34.6	**.50**	36.1	**.69**
3rd "	33.3	**.60**	35.6	**.56**	36.5	**.62**	31.2	**.72**	33.1	**.46**	34.6	**.54**
4th "	32.1	**.59**	34.0	**.72**	35.1	**.48**	30.4	**.64**	31.7	**.60**	33.3	**.50**
5th "	31.1	**.54**	33.0	**.82**	33.9	**.51**	29.5	**.73**	31.2	**.60**	32.4	**.56**
6th "	30.6	**.32**	32.3	**.78**	33.4	**.52**	28.9	**.46**	30.4	**.44**	32.0	**.58**

the other two showing considerable gains. In the curves given in Plate III, p. 471, we can analyze these gains somewhat.

TABLE VI. (Cont.)

Subject II

Days	Rt. Hd. 1–10		Rt. Hd. 11–20		Rt. Hd. 21–30		Lft. Hd. 1–10		Lft. Hd. 11–20		Lft. Hd. 21–31	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
1st Interval	37.2	.88	41.2	.92	42.1	.72	33.7	.75	36.5	.90	37.1	.72
2nd "	35.8	.86	39.5	.88	40.7	.62	31.9	.80	35.4	.56	36.2	.46
3rd "	34.7	.94	38.0	.78	39.4	.40	30.7	.96	34.2	.84	35.2	.42
4th "	33.7	.88	37.0	.84	38.4	.44	30.0	.92	33.2	.58	34.0	.44
5th "	33.1	.80	36.4	.80	37.8	.62	29.4	.92	32.3	.56	33.2	.42
6th "	32.6	.68	36.1	1.00	37.5	.78	28.8	1.06	31.7	.64	32.2	.44

The principal point to be noted in this table is that the practice gain is in Subject I more prominent in the earlier intervals; increase therefore is mainly one of initial efficiency. In Subject II the intervals tend to gain about equally.

The most striking feature about them is that in both subjects the initial interval invariably makes a considerable gain. In-

deed, so far as the initial efficiency is concerned, one could hardly be sure that there would have been greater gain if the practice had been continued throughout the intermission. On the other hand, it is apparent that in Subject I there is much greater susceptibility to fatigue immediately after the intermission ; on the 15th and 27th days all the later intervals lose, and on the 25th day the gain of the later intervals is by no means proportionate to that of the first. Subject II on the other hand, shows a very marked gain throughout all the intervals on the 15th, 25th, and on the 27th days, in every case but one, the fifth interval for the 15th day. Only on the 15th day is any special susceptibility to fatigue indicated, though it is true that the fatigue loss is on each of the three days greater than the average for the group of ten experiments in which each belongs. Both subjects found the sensations of fatigue to be much more marked on the day after an intermission, and indeed these were in Subject I practically the only times when they appeared at all. The great initial gain after the intermissions is by no means easy of explanation. It seems rather forced to interpret it as the result of a renewed "*Neuigkeitsantrieb*," especially for Subject I. It seems to be a fairly general observation, however, that partially practiced co-ordination paths may subsequently become more firmly established during a period of rest ("learning to swim in winter and to skate in summer," etc.). The intermission gain here noted is probably an aspect of this, presumably a physiological phenomenon.

11. *The effect of warming up, as brought out by practice, on the different intervals.* In order to gain some idea of the extent of the warming-up process, it was made the subject of four special experiments, which are not included in the curves. These succeeded immediately upon the twenty-fourth day of practice, and consist each of ten series made with one hand alone. The first and third of these experiments were made with the right hand, the second and fourth with the left, the routine being otherwise the same as in the regular experiments. Inasmuch as these experiments show fairly well the behavior of each hand at a high degree of practice, and illustrate many points in it that would otherwise be impossible to bring out concretely, a right and left hand experiment for each subject is reproduced in full.

These records show immediately that in the right hand at least, the warming-up process is by no means exhausted in the first five series ; on the contrary, the second five series are uniformly better than the first. The individual series improve in rate up to a certain point, and then the warming-up process is no longer sufficient to counterbalance the unrecovered fatigue from series to series, when the series begin to fall off. The

TABLE VII

Experiments of 10 series each upon the same hand throughout of Subjects I and II, after 24 days of practice. The series followed each other at 3′ intervals.

	Subject I. (Rt. Hd.)							Subject II. (Rt. Hd.)						
	1st interval 0″–5″	2nd " 5″–10″	3rd " 10″–15″	4th " 15″–20″	5th " 20″–25″	6th " 25″–30″	Total.		1st interval 0″–5″	2nd " 5″–10″	3rd " 10″–15″	4th " 15″–20″	5th " 20″–25″	6th " 25″–30″	Total.
1st series	40	37	35	34	32	32	210	1st series	41	38	36	36	35	35	221
2nd "	38	38	36	33	33	32	210	2nd "	40	39	38	38	37	36	228
3rd "	40	39	36	35	34	33	217	3rd "	41	40	40	39	38	37	235
4th "	41	39	38	37	35	36	226	4th "	42	41	40	40	40	39	242
5th "	42	39	38	38	36	35	228	5th "	42	42	40	40	38	38	240
6th "	41	40	37	36	36	35	225	6th "	43	43	40	40	40	40	246
7th "	42	41	38	38	36	36	231	7th "	43	42	42	41	41	40	249
8th "	40	41	39	37	35	35	227	8th "	43	42	41	40	41	40	247
9th "	41	39	37	36	35	34	222	9th "	43	42	42	40	40	39	246
10th "	40	38	37	35	34	35	219	10th "	43	41	40	39	39	40	242
Av.	40.5	39.1	37.1	35.9	34.6	34.3	**221.5**	Av.	42.1	41.0	39.9	39.3	38.9	38.4	**239.6**

TABLE VII. (Cont.)

	Subject I. (Lft. Hd.)							Subject II. (Lft. Hd.)						
	1st interval 0″–5″	2nd " 5″–10″	3rd " 10″–15″	4th " 15″–20″	5th " 20″–25″	6th " 25″–30″	Total.		1st interval 0″–5″	2nd " 5″–10″	3rd " 10″–15″	4th " 15″–20″	5th " 20″–25″	6th " 25″–30″	Total
1st series	**39**	**35**	**33**	**33**	**30**	**31**	201	1st series	**36**	**36**	**34**	**32**	**33**	**32**	203
2nd "	**39**	**35**	**34**	**32**	**32**	**32**	204	2nd "	**35**	**36**	**34**	**33**	**33**	**33**	204
3rd "	**40**	**36**	**35**	**34**	**33**	**32**	210	3rd "	**38**	**37**	**37**	**35**	**35**	**34**	216
4th "	**38**	**37**	**35**	**35**	**33**	**33**	211	4th "	**38**	**37**	**36**	**35**	**34**	**33**	213
5th "	**40**	**38**	**36**	**35**	**32**	**34**	215	5th "	**39**	**37**	**36**	**35**	**34**	**33**	214
6th "	**39**	**38**	**35**	**35**	**33**	**32**	212	6th "	**38**	**38**	**36**	**34**	**34**	**32**	212
7th "	**38**	**36**	**34**	**33**	**33**	**31**	205	7th "	**37**	**37**	**35**	**34**	**34**	**31**	208
8th "	**38**	**37**	**35**	**33**	**33**	**32**	208	8th "	**37**	**37**	**36**	**35**	**33**	**33**	211
9th "	**35**	**35**	**32**	**33**	**32**	**31**	198	9th "	**37**	**37**	**34**	**33**	**32**	**31**	204
10th "	**36**	**35**	**34**	**33**	**33**	**31**	202	10th "	**37**	**37**	**35**	**35**	**33**	**31**	208
Av.	38·2	36·2	34·3	33·6	32·4	31·9	**206.6**	Av.	37·2	36·9	35·3	34·1	33·5	32·3	**209.3**

maximum in the right hand is never reached until the seventh or eighth series. In the left, on the other hand, the maximum is reached more quickly, and we see more of the falling off process; this much more clearly in Subject I. The second five series with the right hand are distinctly better than the first five, though in the left hand the reverse is true in the series quoted.

In further examining the records, especially those of the right hand, in which the phenomenon is more clear cut, we see again the point already brought out regarding the more precise character of this warming up gain. It is a gain that affects all the intervals somewhat, but the later rather more than the earlier; *i. e.* the gain comes mainly through an increased immunity to fatigue. Thus we see that while the initial performance of Subject I's right hand increases only from *40* to *42*, the final interval increases from *32* to *36*. In the left hand the initial gain is practically *nil;* that of the final interval from *31* to *34*. The initial interval of Subject II's right hand gains from *41* to *43*, the final interval from *35* to *40*. His left hand, as has been noted, is anomalous with respect to the warming up phenomenon. Here we find the initial intervals gaining, while the final ones tend to lose. This loss is accompanied by considerable sensation of fatigue.

This warming up increase in the later intervals probably persists a considerable time; longer at least than the fatigue that we see gradually lowering the efficiency of the later series. This appeared in a group of subsequent experiments on the right hand of Subject I in which two records of five series each were made within one hour 45 minutes of each other. Table VIII, p. 468, will illustrate this point:

The final intervals in the 3:45 record warm up from **31** to **35**, with a considerable increase also in the initial interval; those of the 5:30 record begin at **34** and warm up to **37**, with negligible increase in the initial interval. Sometimes, also, the final interval does not warm up at all in the 5:30 record; but the essential point is that the final interval in the 5:30 record always begins considerably ahead of that in the 3:45 record. It should be mentioned that series taken at 8:45 A. M., show in all respects the same characteristics as those of 3:45 P. M. on the same day.

12. *An "index of fatigue."* It is of course impossible to obtain a complete view of the fatigue phenomena in any experiment in the absence of the entire curve. But while the record does give us a curve of this sort, it is quite impracticable to evaluate all its factors, and as has been said, we

TABLE VIII
Subject I, Right hand

	3:45 P. M.							5:30 P. M.						
	1st interval 0″–5″	2nd interval 5″–10″	3rd interval 10″–15″	4th interval 15″–20″	5th interval 20″–25″	6th interval 25″–30″	Total.	1st interval 0″–5″	2nd interval 5″–10″	3rd interval 10″–15″	4th interval 15″–20″	5th interval 20″–25″	6th interval 25″–30″	Total.
1st Series	**40**	**37**	**36**	**33**	**33**	**31**	210	**42**	**40**	**37**	**36**	**35**	**34**	224
2nd "	**38**	**37**	**36**	**35**	**34**	**32**	212	**39**	**38**	**36**	**36**	**36**	**34**	219
3rd "	**42**	**39**	**37**	**37**	**35**	**34**	224	**42**	**40**	**37**	**37**	**35**	**36**	227
4th "	**42**	**40**	**39**	**36**	**36**	**34**	227	**42**	**42**	**39**	**37**	**36**	**36**	232
5th "	**43**	**40**	**39**	**37**	**37**	**35**	231	**43**	**40**	**38**	**38**	**37**	**37**	233
Av.	41.0	38.6	37.4	35.6	35.0	33.2	**220.8**	41.6	40.0	37.4	36.8	35.8	35.4	**227.0**

consider merely the amount done in the successive 5″ intervals. This together with the inspection of the record, will give a very fair idea of all but the finest fluctuations. And yet when we consider the number of individual curves with which we have to deal it will readily be seen that it is impossible to state the phenomena even at this length in their entirety. All things

taken into account, it is probably best that we should use some single figure as the expression of fatigability. This figure, which is here used as the "index of fatigue" and which will subsequently be denoted by *f*, is calculated by taking the average number of taps executed in the 2d, 3d, 4th, 5th and 6th intervals, and dividing it by the number of taps executed in the first interval. Thus, a curve may run as the first one in the type experiment on p. (438), *41, 37, 35, 34, 34, 32*. The number of taps in the first interval being *41* and the average number in the remaining five intervals being 34.4, *f* equals $\frac{34.4}{41.0}$ or .85.

This figure gives us the gross amount of decrease in rate during a certain period, though, of course no idea as to the form or speed with which the decrease sets in. Its main arithmetical source of error is that the number of taps made in the first five seconds is rather coarse on account of being given in the form of an integer, its probable error being about half a tap each way. *The higher the f the greater the immunity to fatigue; the lower the f the greater the susceptibility.*

13. *Correlation of the fatigue phenomena in the different hands.* All statements of individual differences, correlations, etc., in fatigability, are made upon the basis of this *f*. It is possible in a measnre to test the validity of the *f* by comparing the results with the right and left hands. The results of the ten subjects show a slight tendency for the individual who is fatigable with his right hand to be also fatigable with his left, and for the day of greater fatigability with one hand to correspond to the day of greater fatigability with the other.

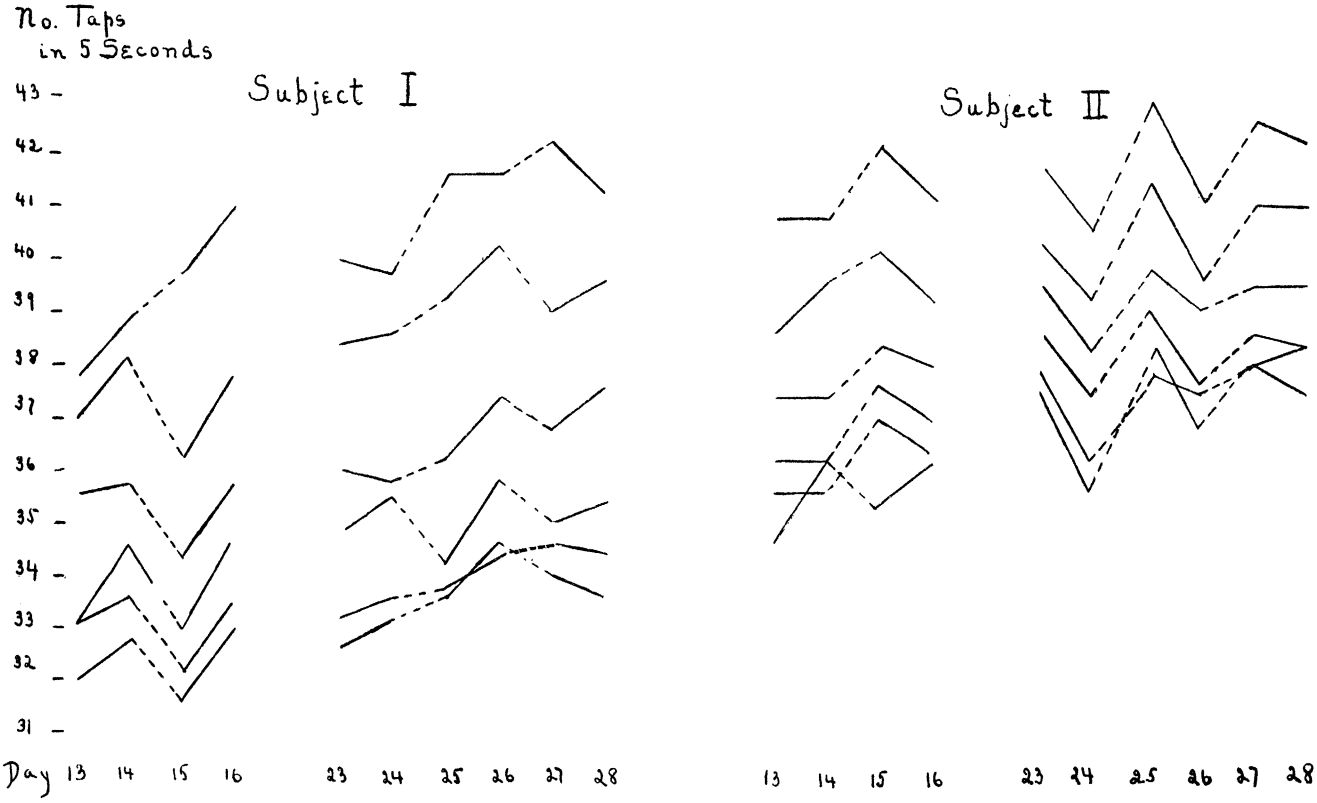
It has already appeared, however, in other aspects of the results, how much the delicacy and responsiveness of the test is increased by practice. The results of the practised subjects seem to indicate a greater correspondence between the fatigability of right and left hand than is found in the ten normal subjects, though even here the conclusion depends somewhat upon the method by which we treat the data. Taking the average *f* for the five series of each day as most representative of the *f* for that day, we have for the thirty experiments thirty *f*'s for each hand. Arranging the thirty *f*'s for the right hand in order of size, and comparing this order with that of the left hand, we find between them 37% of displacements for Subject I, 43% for Subject II.[1] This is again but

[1]With reference to this correlation method *cf.* Ruediger, The Field of Distinct Vision, *Arch of Psych.* 5, pp. 37-8; Wells, A Statistical Study of Literary Merit, *Arch of Psych.* 7, p. 23.

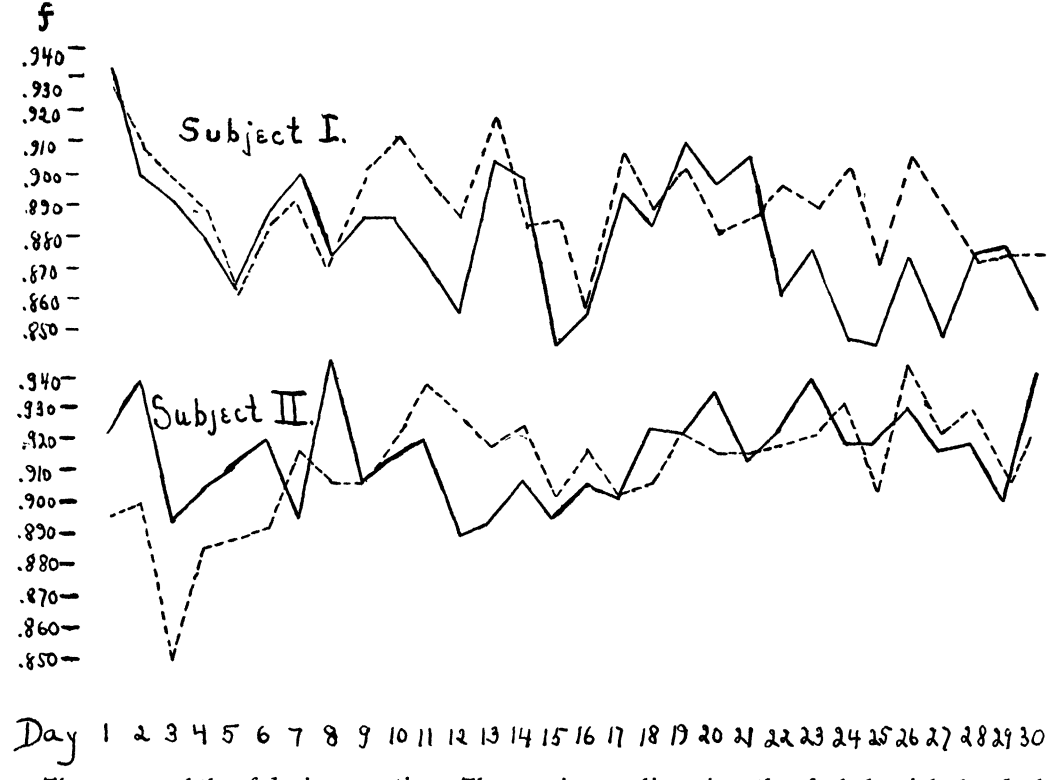
a small positive correlation. We may also observe whether the right and left hands tend to increase or decrease together from day to day; this seems to the writer perhaps the most logical way of treating data of this precise nature. We may plot curves of the f's of the right and left hands for different days, and superpose them. This gives us the figure in Plate IV. In examining these curves, we may note that with respect to ascent or descent the left hand follows the right with considerably more frequency than is provided for by chance. The chance correspondence would be 14.5, 50% of the cases; it actually occurs in 22, 76% of the cases for Subject I, and 21.5, 74% of the cases for Subject II, as can be seen by the study of the curves. It may be noted that the fewer negative and zero cases are more likely to be extreme than the more numerous positive ones, *cf.* days 15, 24 and 28 for Subject I, and 7 and 8 for Subject II. This would again suggest that the negative relationships were the product, not of chance variation, but of the intercurrence of uncontrollable conditions affecting one hand especially. To the extent to which positive correlation between right and left hand exists, the measure is one of a general condition; for the rest it refers only to the specific neuro-muscular mechanism involved in the movements of either hand.

In the face of these indisputable cases of the right hand showing one extreme, the left the other extreme of fatigability, and this in a test of such high mathematical precision as the present, it is plain that we must either postulate a considerable influence of the work of one hand upon that of the other or else largely give up the measure as an index of a general fatigability. In a few instances, especially in the later practice of Subject I, the former possibility would seem justified, but there are still marked cases as that of the 8th day in Subject II which cannot be explained in this way. While, then, the two hands do seem to have a tendency to correlate positively, each hand seems also to be subject to so many effects specific to itself—irrelevancies, as Spearman would call them—as largely to limit the value of the single measure as a general measure. And we cannot be sure that the fatigue phenomena of different functions, as the tapping test, the ergograph and the addition test, would exhibit a traceable correlation, at least in normal individuals.

14. *The relative fatigability of right and left hands.* There seems to be no regularity in the relative fatigability of right and left hands among different individuals; in some the preferred, in others the unpreferred hand shows the greater immunity to fatigue. More frequently, however, we find that the preferred hand has the greater immunity to fatigue, and



Records of the right hand on the days immediately preceding and following intermissions, which are given in dotted lines. There is an unrecorded practise of 20 series during the intermission before the 25th day (unrecorded in the curves), succeeding immediately upon the 24th day. (*Cf.* p. 464.)



The course of the *f* during practise. The continuous line gives the *f* of the right hand, the dotted line the *f* of the left hand, in both subjects. These curves show the general effect of practise on fatigability, as well as the relationship of the two hands.

this is the relationship which obtains in the averages for the ten normal subjects. The relationships in the two practiced subjects can be best seen by again referring to Plate IV. In Subject I the fatigability of the right and left hands is about equal at first, in Subject II the left hand is much more susceptible than the right; but it will be seen that the effect of practice is in both subjects to immunize the left hand to fatigue more than it immunizes the right.[1] In Subject II they end about equal. A possible interpretation of this fact is as follows: Practice diminishes fatigue sensations, and since the left hand is more subject to fatigue sensations than the right, it probably diminishes those of the left more than it does those of the right. If, then, fatigue sensations have an inhibiting effect on the tapping rate, the result is entirely what we should expect. But it must be remembered that in this experiment the relation between fatigue sensation and fatigue of performance is only an indirect one. In the ergograph it is the muscle which does the work, and the muscle which shows the fatigue sensations; but in the tapping test there is every reason to believe that the muscles would, during any fatigue conditions that are reached in the present experiments, execute an indefinite number of taps if only they received the innervations fast enough. The objective fatigue phenomena which we note in the test are in all probability either a fatigue phenomenon in the refractory phase or a lowered efficiency of co-ordination, equally a product of altered synaptic conditions; the sensations of fatigue on the other hand, may with equal assurance be ascribed to tissue changes within the muscles that take place as a result of their continued effort. In this test, therefore, the fatigue sensations are absolutely no indication of the actual fatigue conditions, and any traceable correspondence between fatigue sensation and fatigue of performance must be regarded as almost wholly a product of reflex inhibition. In this way we can perhaps judge something of the relative responsiveness of the two subjects to sensations of fatigue. As noted, sensations of fatigue are in both subjects especially prominent the day after an intermission, but Subject II shows no special objective susceptibility on such days, Subject I a great deal. By itself, this result could be taken to mean that Subject I was more responsive to sensations of muscular fatigue than Subject II. But, on the other hand, Subject I had practically no sensations of

[1]The question is actually more complicated than appears here, involving in Subject I certain questions of the relation of warming up, practice and fatigability; but the matter is rather too complex in proportion to its importance to detail here, further analysis seeming to justify the same result as appears superficially.

fatigue except on such days, and naturally responded to them more when he perceived them than when he did not; while II was considerably subject to them throughout the experiments, especially in the left hand. Then, too, there is no other way of gauging the relative intensity of the fatigue sensations in the two subjects, or the extent of the physiological processes which bring them about. In this connection it must also be noted that I while considerably less subject to fatigue sensations than II is distinctly more subject to actual fatigue losses than II. The figures, as well as those for the 10 subjects, are shown in the following table:

TABLE IX

Relative Fatigability of Right and Left Hands in the Different Subjects

	10 Normal Subjects	Subject I			Subject II		
		Days 1–10	11–20	20–30	1–10	11–20	21–30
Rt. hd.	.912	.890	.882	.870	.915	.912	.922
Lft. hd.	.897	.895	.892	.884	.896	.918	.924

Taking as the unit the average f in each experiment, the m. v.'s of the above quoted averages are for the normal subjects .038 and .030 respectively; for the practiced subjects they range between one-fourth and two-thirds as much, being considerably smaller for Subject II.

15. *The correlation of fatigability and initial rate.* A further question presents itself in the relation of fatigability to initial rate. Each individual has a normal initial efficiency and susceptibility to fatigue, and it is the relationships of the variations of the individuals about these norms that we ought to consider. We may first give the relationships as indicated in the records made by the same individual, but on different days. In the two experiments on each of the ten subjects the day of greater initial efficiency corresponded to the day of a greater f in but 5% of the cases with the right hand, and in 35% of the cases with the left hand. In the practiced subjects, only the records for the first ten days are considered. In Subject I the correspondence of initial rate and f is 0% plus signs for the right hand, and 15% plus signs for the left; in Subject II 20% plus signs for the right hand and 45% plus signs for the left.

In examining now how the relationship subsists between the different series executed by the same subject on the same

day, we find that the negative relationship is here more clear cut than previously. We should indeed expect this, because this is the case in which the data to be compared are obtained under more closely corresponding conditions. We find that the series with the best initial rate of a single record tends also to be the most fatigable series in that record. Perhaps the matter may be more clearly brought out by the following (rather extreme) example, which is from the record of subject E.'s right hand in his second experiment:

TABLE X

No. taps in 1st Interval

	Initial rate.	*f*
1st Series	41	·77
2nd "	36	.87
3rd "	35	·93
4th "	42	·79
5th "	41	.81

It is quite obvious that the 1st, 4th, and 5th series, which have a high initial rate are also in a class by themselves in great susceptibility to fatigue, as opposed to the 2d and 3d series, which have a low initial rate, and show much less fatigue. Calculating the per cent. of like signs relationship for all the records, we obtain an average for the ten subjects of 20% plus signs for the right hand, and 21% for the left; in the practiced subjects, I gives 15% plus signs for the right and 25% for the left, II gives 32% for the right and 20% for the left. This last is the only instance in which the right hand does not give the more pronounced correlation.

We thus observe a general tendency to negative correlation between initial rate and *f*, thus of course a positive one between initial rate and *susceptibility* to fatigue. This is what we should ordinarily expect; "he who runs fast, will not run long."

16. *The effect of practice on fatigability.* The general effect of practice on the *f* have already been observed in Plate IV. In Subject I practice appeared to increase susceptibility; in Subject II there was rather increased immunity. As given in terms of *f*, the results are also seen in the gross by referring

to Table IX. The way in which practice affects fatigue in the different series affords, however, an additional point of some interest. These figures, for the three groups of ten experiments with each hand, are given in the following table:

TABLE XI

Practice and Fatigability

Average f for each series in two Groups of ten experiments

Subject I

Rt. Hd.

Days....	1–10		11–20		21–30	
	Av.	M. V.	Av.	M. V.	Av.	M. V.
1st Series	.884	**.022**	.873	**.025**	.861	**.019**
2nd "	.910	**.016**	.886	**.024**	.865	**.017**
3rd "	.884	**.035**	.887	**.025**	.866	**.016**
4th "	.881	**.015**	.882	**.026**	.875	**.027**
5th "	.893	**.009**	.883	**.025**	.879	**.017**
Av.	**.890**		**.882**		**.870**	

Lft. Hd.

1st Series	.893	**.019**	.868	**.018**	.865	**.019**
2nd "	.912	**.018**	.909	**.023**	.890	**.014**
3rd "	.895	**.027**	.890	**.018**	.889	**.017**
4th "	.895	**.025**	.900	**.029**	.893	**.024**
5th "	.880	**.032**	.889	**.018**	.885	**.017**
Av.	**.895**		**.892**		**.884**	

TABLE XI. (Cont.)

Subject II

Rt. Hd.

1st Series	.902	**.026**	.890	**.022**	.896	**.014**
2nd "	.917	**.015**	.921	**.018**	.928	**.008**
3rd "	.915	**.021**	.920	**.010**	.924	**.013**
4th "	.923	**.022**	.907	**.023**	.930	**.019**
5th "	.917	**.037**	.911	**.019**	.934	**.014**
Av.	**.915**		**.912**		**.922**	

Lft. Hd.

1st Series	.892	**.026**	.904	**.012**	.910	**.012**
2nd "	.911	**.017**	.938	**.022**	.941	**.019**
3rd "	.887	**.030**	.916	**.016**	.935	**.026**
4th "	.889	**.019**	.920	**.012**	.916	**.022**
5th "	.901	**.017**	.909	**.021**	.914	**.015**
Av.	**.896**		**.918**		**.924**	

The general tendency of these tables, except always in the left hand of Subject II is that practice establishes throughout an immunity to fatigue that is progressive through the five series. We saw this illustrated in detail in the records of 10 series of one hand above printed in full (Table VII), and we can observe here how this relationship is brought out by practice. The *f*'s uniformly become larger as the later series are reached, and in later practice this tendency is much more marked than at the beginning. It is of course, another phase of the warming up process. Another point is the very low susceptibility to fatigue that is throughout prominent in the second series. By referring to Table V we see that this is also associated in the left hand with a relatively low gross rate,

though not so much as in the right. The reason for this is a rather interesting one. The *f*, as has been said, is calculated from the initial interval. Now it happens that in the second series, the initial interval is always abnormally slow; always a tap or two slower than the first, and from three to five taps slower than the later series. On the other hand, the warming up process in the later intervals is strikingly in evidence in the second series, and it is this that beside raising the gross rate of the series makes it show immunity to fatigue. This point is also very strikingly shown in Table VII. As may be seen, the uniform tendency in all four records is for the first interval of the second series to be as small or smaller than the first interval of the first series, while the second interval of the second series is as great or greater than the second interval of the first series. The figures are reproduced in Table XII, p. 479.

By comparing the performances during the first two intervals with the total, one can easily see how much more the second series resists fatigue than the first, even when, as in the left hand of Subject I, this resistance is not evident so early as the second interval. Why the first interval alone in the second series should be slower than that in the first series, and the remaining intervals uniformly faster, is difficult to say, but of the general tendency there can be no doubt; it is present throughout the thirty experiments on each practiced subject, as well as quite generally in the ten unpracticed subjects. It would seem as though the warming up affected the later intervals first, and only subsequently extended its effect to the initial one.

On account of the influence of practice in establishing this warming up process, it would seem fairer to judge of the specific effect of practice on fatigability on the basis of the first series only in each record, because these have no warming up series behind them. Referring to Table XI it is evident that the immunity to fatigue as given in *f* tends with practice to decrease more, or to increase less, in the first series than in any of its followers. Indeed, the 2nd series in the right hand of Subject I, and the 5th series in the left hand of Subject II are the only exceptions to this generalization. It would seem therefore that the specific effect of practice on fatigability is in the nature of an increased susceptibility rather than an increased immunity. The increased immunity shown in the averages of Plate IV and Table IX is largely a product of the increased immunity of the later "warmed up" series. *The true practice gain is one mainly in the initial efficiency of performance, as distinguished from the warming up gain, which shows itself chiefly in continued efficiency of performance.*

It is interesting to compare the effect of practice with that

TABLE XII

	Subj. I, Rt. Hd.			Subj. I, Lft. Hd.			Subj. II, Rt. Hd.			Subj. II, Lft. Hd.		
	0"–5"	5"–10"	Total No. Taps in Series	0"–5"	5"–10"	Total No. Taps in Series	0"–5"	5"–10"	Total No. Taps in Series	0"–5"	5"–10"	Total No. Taps in Series
1st Ser.	**40**	**37**	210	**39**	**35**	201	**41**	**38**	221	**36**	**36**	203
2nd Ser.	**38**	**38**	210	**39**	**35**	204	**40**	**39**	228	**35**	**36**	204

of age. Both, as may be accepted as certain, tend to increase the rate, and it increases from childhood to adolescence con-

siderably more than it does in the practice of the two adults here tested. In their effects on fatigability, however, the two are somewhat divergent. The effect of increase in age is almost certainly to increase immunity while the above mentioned specific effect of practice, *i. e.*, warming up factors excluded, seems to be to decrease it, or at least to give but very small increase. The modifications in the behavior of the tapping test with increasing age must then in a certain measure be ascribed to different factors than those operative in practice improvement.

17. *Variability.* While no average has been quoted whose m. v. has not been calculated, no great stress has been laid on variability in the preceding paragraphs, and it may therefore have a special mention here. In the present experiments the practically universal effect of fatigue on variability is in the nature of a decrease. This appears between individuals (p. 451) in the records of the practiced individuals from day to day (Table VI, pp. 462-3), and also in the records made by the same individual on the same day. There is so much interaction between warming up and practice that no conclusions regarding a specific effect of these factors on variability can be drawn. There is, however, a general tendency for the m. v.'s of the left hand to be smaller than those of the right.

This last aspect of the results is one that may be compared with certain findings of Bryan; for the most part Bryan's results are not so strictly comparable with the present on account of their averages always dealing with groups, not with individuals. However, there seems also in these findings to be a greater variability in the right hand than in the left. The individual differences in gross rate, which are here expressed in the standard deviation instead of the m. v., show on the whole a greater variability for the right hand; it will be remembered that this was also slightly the case in the present experiments. It also appeared that the year to year fluctuations in rate (among different subjects) were somewhat greater for the right than for the left hand. Although the results quoted can hardly establish the point conclusively, yet it is true that we should probably expect the hand that more nearly reflects the individual's maximum ability to vary more in its ability. In this connection it may be mentioned also that there was no significant difference in the year to year increase in the two hands; this may be compared with the result in the present study that in practice also the right and left hands tended to gain about equally.

18. *The subjective condition as related to gross rate and fatigability.* On each day of the thirty experiments, Subject I graded the general condition introspectively as *A* relatively

good, *B* above medium, *C* below medium, *D* poor. Needless to say, the grade was assigned before the experiment was begun. In all, there were thus assigned 3 *A*'s, 12 *B*'s, 14 *C*'s and 1 *D*. It was desired to see if the grade subjectively assigned tended to correlate in some degree with the gross rate, the fatigability, or other aspect of the test. So far as can be seen, the first relationship is quite chaotic. For example the best performance was made on a *C* day; the performance of the *D* day while not very good in the gross, had the highest initial rate reached yet, and followed three days after an equally poor record made on an *A* day. It would seem therefore that while the daily performances are entirely definite facts and represent such and such a physiological condition with relative precision, this condition is not one that influences the subjective estimate to any appreciable degree. The character of the warming up gain does not seem in any way related to the subjective estimate, nor, it may be mentioned, do the present experiments bear out the correlation suggested in Bolton's figures between general superiority and the presence of interserial warming up. In the index of fatigue, however, a certain relationship is indicated; but, strange to say, it is in the direction of the good days being more fatigable than the poor ones. If we consider only the last twenty days, during which the *f* is no longer subject to practice decrease, as well as the gradings being better distributed, the two remaining *A* days have an average *f* of .86, m. v. 0; the seven *B* days .875, m. v. .010; the ten *C* days .881, m. v. .019. Including the entire thirty days, the *C* average is slightly below the *B*, on account of the low susceptibility of the first few days, uniformly graded *B*; the *A*'s remain at .86. The single *D* day has the lowest *f* recorded, .84; but this is because it came on the 15th day, immediately after a two week's pause, when susceptibility is always greatly increased; it may be mentioned also that this *D* was assigned mainly on the basis of somatic sensations, which were those of marked weariness. If the result is significant, the following are two possible interpretations; the subjective estimate may have been the direct product of physiological conditions which really involved greater susceptibility to fatigue, and, owing to a good subjective condition the subject may have put forth nearer his physiological maximum of effort, and consequently fatigued more. From these considerations it follows as a corollary that the initial rate, or best performance for 5″, corresponds more closely with the subjective estimate than does the gross rate for 30″—on account of the observed relationship of high initial rate, low index of fatigue (*i. e.* high fatigability).

The principal findings of the present study may be thus presented under the various headings as given at the beginning:

1. The extremes of individual variation for 10 unpracticed subjects' rates were in initial rate approximately 2:1, in the gross rates for 30 seconds about 3:2; but it does not appear that this difference is related to general quickness, and beyond efficiency of co-ordination it is not known upon what neural condition it does depend.

2. The index of right-handedness varies between .81 and .94, and though subject to a good deal of variation in the individual, is yet a distinct point of individual difference.

3. With the 2′ 30″ rest-periods used, the right hand of unpracticed subjects tends to increase (warm up) in rate through the five successive series; but this is not so clear in the left hand.

4. After the first few seconds, the rate in the individual series progressively decreases, having, on an average, some six-sevenths as much speed during the last five seconds as in the first five.

5. The fatigue in the tapping test induced by a 30″ performance tends progressively to decrease individual differences in ability for the test.

6. For two normal individuals, the practice curve is everywhere gradual in ascent. The curve fluctuates more from day to day after a week of practice than at the beginning.

7. The left hand does not improve by practice more than the right. Practice tends to increase the m. v. of the five series of each day's performance.

8. Practice brings out the warming up phenomena (*i. e.*, the gain of later series over the earlier) to a marked extent. Next to the gross gain, this is the most important aspect of the practice effect.

9. In Subject I, practice improves the initial interval of the series more than the later; in Subject II all intervals share about equally in the practise gain.

10. Intermissions of two weeks or less have no unfavorable effect on the practice gain, beyond at first increasing fatigue sensations.

11. Warming up shows itself mainly in an increased immunity to fatigue, *i. e.*, the later intervals increase more than the earlier. Its possibilities are by no means exhausted in the five series uniformly taken; it may persist for three or four series further.

12. The ratio of the first to the average of the later intervals furnishes a convenient "index of fatigue" (f), through which to observe quantitative relationships in susceptibility and immunity to fatigue.

13. There is only slight tendency to positive correlation in the fatigability of the different hands.

14. The right hand is ordinarily more immune to fatigue than the left; but there are individual exceptions. Practice tends to affect average *f*'s of the left hand more favorably than those of the right. The fatigue sensations are not the product of any factors directly concerned in the speed of repeated movements, and any special correspondences noted between fatigue sensation and actual fatigue loss is the result of reflex inhibition. Of the two subjects, the one more liable to fatigue sensations was less liable to objective fatigue loss. Practice tended to decrease immunity to fatigue in this subject, and to increase it in the other subject.

15. Initial rate and fatigability are negatively correlated, a fast initial rate being usually accompanied by a high fatigue loss.

16. In practiced subjects, the later series of each single record are more immune to fatigue than the earlier, owing to the warming up gain, which affects the later intervals of each series more than the initial. (*Cf.* 11.)

17. Fatigue tends in all respects to decrease variability; no consistent effect on variability due specifically to warming up or practice can be traced. The m. v.'s of the right hand results tend to be larger than those for the left hand.

18. The subjective condition as estimated by an individual practiced in introspection bore no traceable relationship to the gross rate; it seemed, however, that susceptibility to fatigue was greater when the grade assigned was good than when it was poor.